Column by the University Transformer Research Alliance (UTRA) www.university-transformer-research.com

Vibration-measurement-based condition monitoring

20 years of efforts to develop a power transformer monitoring system

ABSTRACT

Vibrations of the transformers are complex multi-physics phenomena that require a deep understanding of electromagnetic and mechanical principles. Their analysis can be used to assess the condition of the transformer in terms of mechanical fixation quality, buckling or ageing of the components. The article presents the 20 years of efforts of researchers in Xi'an Jiaotong University and The University of Queensland on transformer vibration characteristics and its application in the winding mechanical condition monitoring.

KEYWORDS

broadband signals, frequency, modal analysis, monitoring, vibration

1. Introduction

Transformer vibrations mainly come from the core and windings. Previously, vibrations of the iron core were identified as the main source. With the improvement of design and manufacture, especially the use of Hi-B silicon steel sheet, the adoption of step-lap cores, and the reduction of the

Transformer vibrations mainly originate from the core and windings, and they are determined by the capacity, silicon steel materials, structural design, and by magnetic flux density fields

flux density, the cores' vibration has been reduced significantly, and windings' vibration caused by load current becomes a considerable contributor [1]. With time, the size of transformers has increased significantly both in capacity and voltage, resulting in an increase in the vibration of large power transformers. Besides the capacity, vibrations are determined by silicon steel materials, structure design, and magnetic flux density. Therefore, a comprehensive understanding of the vibration generation and transmission in power transformers is necessary.

A transformer's winding modal characteristics (e.g., natural frequencies, mode shapes) are largely determined by its structural stiffness and mass distribution. Changes in the transformer's winding condition can be reflected from the changes in all or a subset of its oscillatory modes. Most of the previous analyses have focused on discrete frequencies (e.g., multiples of power frequency) of the measured vibration signals for assessing the winding mechanical condition. Hong Zhou proposed a winding vibration with the electromagnetic force analysis to obtain the steady-state vibration distribution of the axial direction [2]. Kaixing Hong used the principal component analysis (PCA) to extract vibration features from multi-sensor vibration signals [3]. He also put forward a classification model based on the support vector machine (SVM) to identify the mechanical condition of the windings [4, 5]. Bartoletti used the total harmonic distortion (THD) to identify the health condition of the transformer winding [6]. Bagheri proposed a regression model and a diagnostic criterion based on THD to monitor the inter-turn fault with the Internet of Things (IoT) technology and cloud computing, respectively [7, 8].

Other than the diagnosis based on discrete frequencies, Shao et al. introduced a method to acquire the FRFs under the currents with different frequencies [9]. Wang et al. proposed a similar method [10]. These two methods required a current or a voltage amplifier to generate a frequency-variant excitation. Instead of using the frequency-variant excitations, several researchers have analysed transient vibration signals [11, 12]. S. Banaszak and E. Kornatowski analysed the dependency describing the changes of the normalised power spectral density (PSD) to distinguish the core and the windings conditions in the steady-state and the transient energising process [13, 14].

In the past decade, researchers in Xi'an Jiaotong University and The University of Queensland have been working together to investigate the vibration characteristics of power transformers and develop vibration measurement-based condition monitoring of transformer windings. Their work focuses on three main aspects (1) investigating the sources and significances of different type excitation; (2) extracting and analysing modal characteristics from measured vibration signals; and (3) inferring the changes in winding mechanical condition. This article presents key findings in these three aspects.

2. Where does the internal vibration originate?

In power transformers, the vibrations have been found to originate from (1) the core vibration from magnetostriction of the rolling direction (RD) and transverse direction (TD) of grain-oriented (GRO) silicon steel sheets; (2) periodical Maxwell stress between silicon steels in the joint area of limb and yoke due to flux density arising in air-gap regions; and (3) the winding vibration under electromagnetic forces. The three originations are shown in Fig. 1.

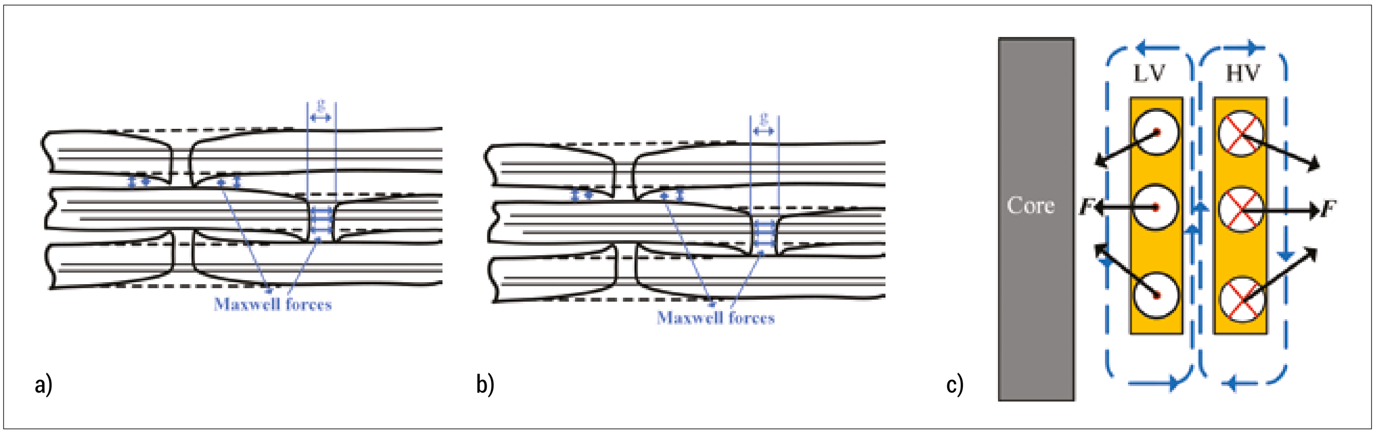


Figure 1. Vibration generation inside power transformers - a) magnetostriction on the RD and TD of silicon steel sheet [15], b) Maxwell forces in the joint region [16], c) electromagnetic forces on windings

Origin of the vibrations in transformers are magnetostriction in the core steel, Maxwell forces in the joint region, and electromagnetic forces on windings

2.1 Core vibration

The magnetostriction of the GRO steel sheets is highly anisotropic. Among the rolling, transverse, and normal directions, the magnetostriction in rolling and normal directions is sensitive to the changes of magnetic flux in the transverse direction. Since the magnetic flux turns 45 ° from the rolling direction of silicon steel sheets in the joint region, the magnetic flux density in the transverse direction in these regions is large. Hence, the excitation in the joint region is always significant compared to other regions, as shown in Fig. 2.

As the magnetostriction and Maxwell forces are both functions of magnetisation vector, the nonlinear magnetisation of GRO brings a significant phenomenon to the core vibration that the vibration harmonics increases dramatically with the increasing voltage (flux density) and locate at multiple times of power frequency. The typical vibration spectrum of the core under different voltages is shown in Fig. 3. It can be seen that the vibration harmonics increase with the increasing voltage. At the 50 % and 75 % of the rated voltage, the 100 Hz vibration component is the maximum. However, when the transformer operates at 100 % of the rated voltage, the 200 Hz vibration amplitude becomes the maximum and the higher harmonics increase significantly.

2.2 Winding vibration

Winding vibration can be caused by Lorentz forces resulting from the leakage magnetic field and mainly vibrates at twice the power of frequency. Influenced by the nonlinear stress-strain characteristics of insulation material (e.g., pressboard, spacer, insulation paper), winding vibration under load current shows obvious vibration harmonics. The winding vibration can be obtained in a load test where one of the windings is excited with voltage, and the other is in short circuit. The excitation voltage is determined by the short circuit impedance. The winding vibration at different load currents is shown in Fig. 4. It can be observed that the 100 Hz and 200 Hz vibration amplitudes increase with the increasing currents.

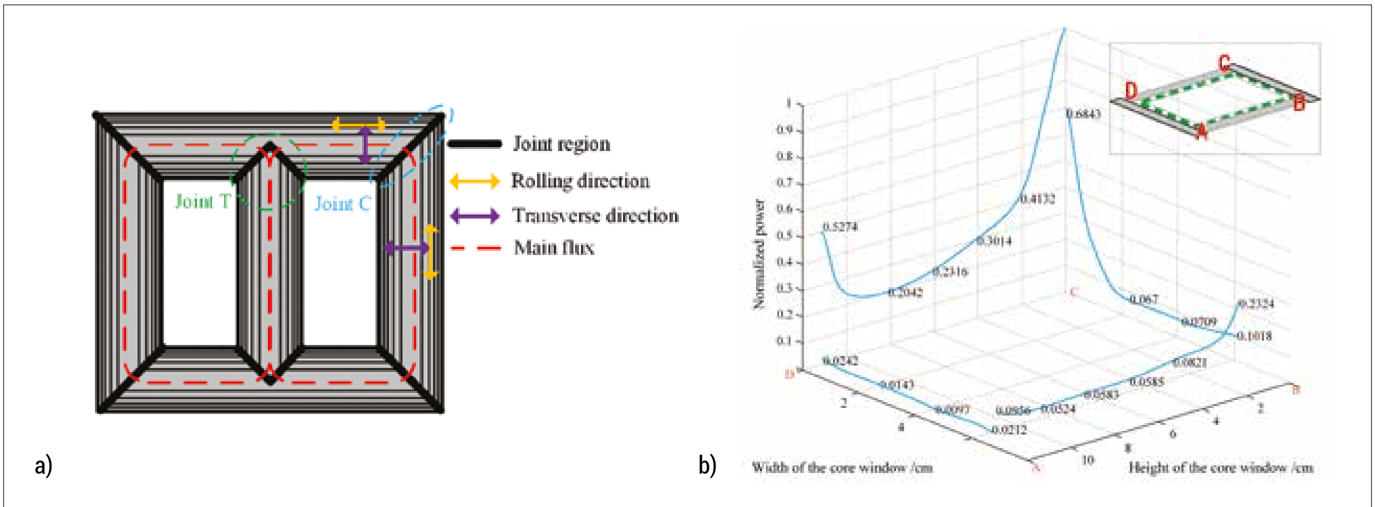


Figure 2. a) Structure of the transformer core, b) distribution of the normalised vibration power along with the core window

3. Coupling vibration between windings and the core

Some researchers assumed that the vibrations of the core and windings are independent of the voltage and current excitation, respectively. In this case, they regarded that the core and the windings are the only vibration sources inside transformers in the no-load test and load test, respectively. However, as the core and windings are connected through the clamping frame, their vibrations are strongly coupled. Fig. 5 presents the acquired winding vibration signals through an optical accelerometer. It can be seen that the maximum winding acceleration is at 200 Hz in the no-load test, which is different from the results that the amplitude at 100 Hz is larger than that at 200 Hz in the load test. The higher 200 Hz vibration component is due to one of the natural frequencies of windings being close to 200 Hz (explained in the next section), approaching the frequency of the core's vibration.

Considering the vibration coupling between the core and windings, it is reasonable to attribute the overall vibration pattern to the load vibration and no-load vibration according to their excitation instead of regarding the windings as not vibrating in the no-load test. This coincides with IEC 60076-10, where the load noise and no-load noise are used. The above coupling mechanism makes the core work as a vibrating source to the windings due to the stiffness and mass of the core being higher than that of the windings. Hence, even if there are small current amplitudes flowing through the windings in the no-load test, the winding vibration can not be ignored because it vibrates under the excitation of the core vibration. In other words, the vibration of the core and the windings should be regarded as an overall entity. It makes no sense trying to separate the core and windings' vibration signals through the mixed vibration signals obtained from the tank.

4. Modal characteristics of windings and tank

Apart from the influence of excitation characteristics, the modal characteristics (e.g., natural frequencies, mode shapes), which are largely determined by its structural stiffness and mass distribution,

Due to highly nonlinear effects, the maximum harmonic component of the core vibration at nominal voltage is 200 Hz for a 50 Hz transformer

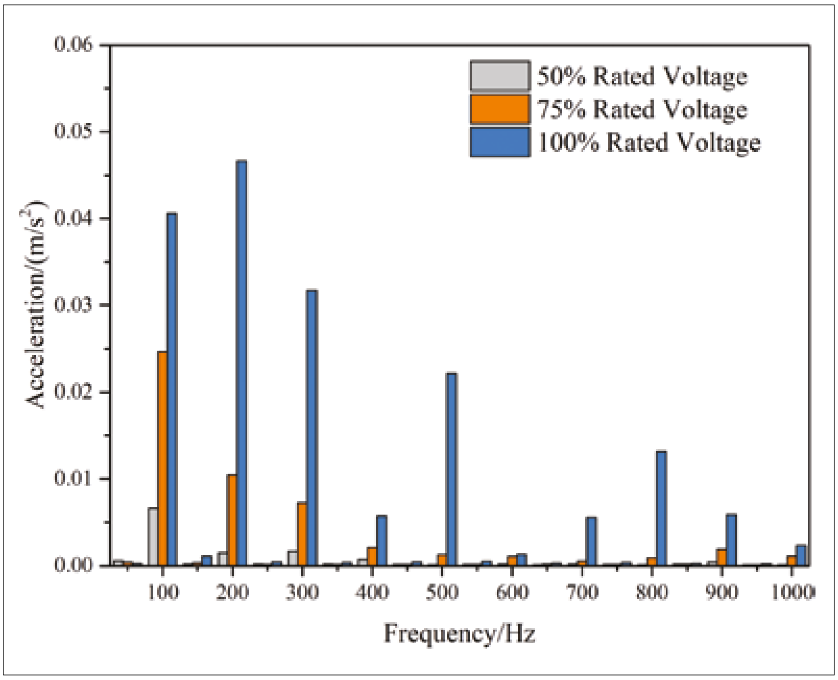


Figure 3. The spectrum of core vibration under different voltages

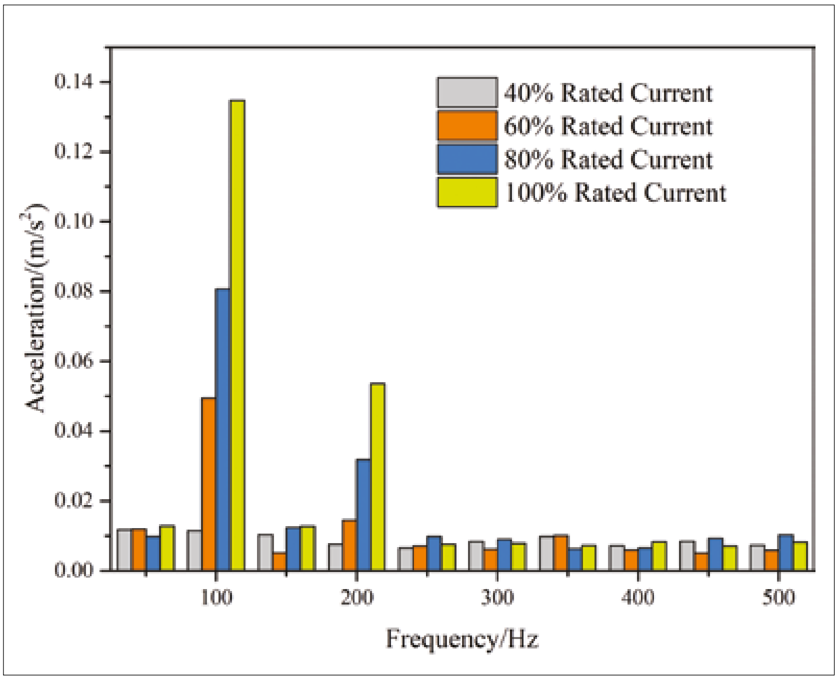


Figure 4. The spectrum of core vibration under different voltages

Winding vibration is caused by Lorentz forces resulting from the leakage magnetic field and mainly vibrates at twice the power of frequency

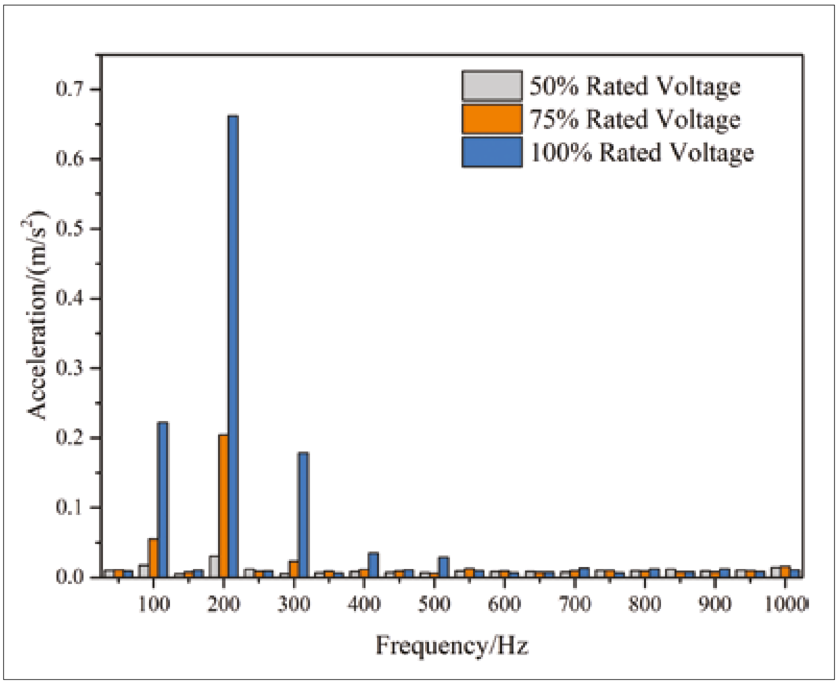


Figure 5. The spectrum of winding vibration in the no-load test

The knowledge about the modal characteristics is critically important to analyse a transformer's vibration because they act as the filter from the excitation forces to the vibration response

The core and windings are connected through the clamping frame, and their vibrations are strongly coupled which should be taken into account in the analysis of the transformer's vibration

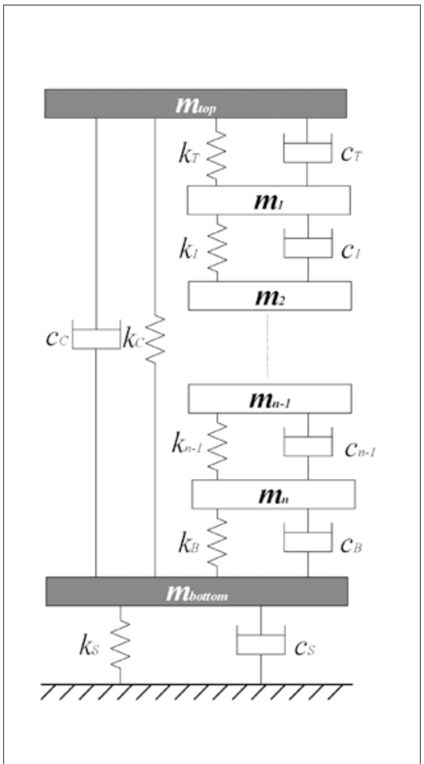


Figure 6. The mass-spring-damping model for describing the winding axial vibration [17]

can affect the vibration characteristics of the transformer. Based on the linear vibration theory, the modal characteristics work as filters which can modify the input excitation according to their inherent responses. Therefore, knowing the modal characteristics is critically important to analyse a transformer's vibration. In the disk-type windings, the winding disks are placed axially and separated by spacers. The combination of hard conductors and soft spacers makes the structure be represented as mass-spring-damping models, as shown in Fig. 6. An example of the first four mode shapes calculated from the mass-spring-damping model is shown in Fig.7, where the first mode (243.9 Hz) shows all winding disks vibration in the same direction, while the second mode (496.39 Hz) shows that the upper part and lower part of the winding vibrate in the opposite directions.

The model presented in Fig. 6 is useful for describing the winding vibration characteristics in air. However, when the windings are immersed in transformer oil, a significant decrease in natural frequencies and an increase in damping can be observed, which is due to the fluid loading effect between the coupling of fluid and structure. A comparison of the windings' natural frequencies in air and oil, which were obtained from the experimental modal analysis of a single-phase power transformer, is shown in Table 1. The first three natural frequencies of the winding in the air are 83.276 Hz, 170.2 Hz, and 243.82 Hz, respectively. After the winding is immersed with the transformer oil, its first three natural frequencies drop to 70.211 Hz, 146.94 Hz, 184.5 Hz. Other than the decrease of natural frequencies, the mode shapes remain the same.

In the oil-filled transformer tank, the thin tank plate can easily be influenced due to the fluid loading effect. To understand its modal characteristics, a finite element model with structure-acoustic coupling is necessary. In this model, not only the static deformation of the oil-filled tank but also the mode shapes of the tank can be obtained. Typical results about the static deflection caused by gravity and the mode shapes of the oil-filled tank are shown in Fig. 8. The deformation of the oil-filled tank caused by the static oil pressure is 2.16 mm, located at the middle of the lower tank surface. The mode shapes at 80.233 Hz and 126.15 Hz are respiration modes [19]. However, influenced by the static oil pressure, the deformation of the tank along the height is non-uniform.

Combining the generation and propagation of the internal vibration, the tank

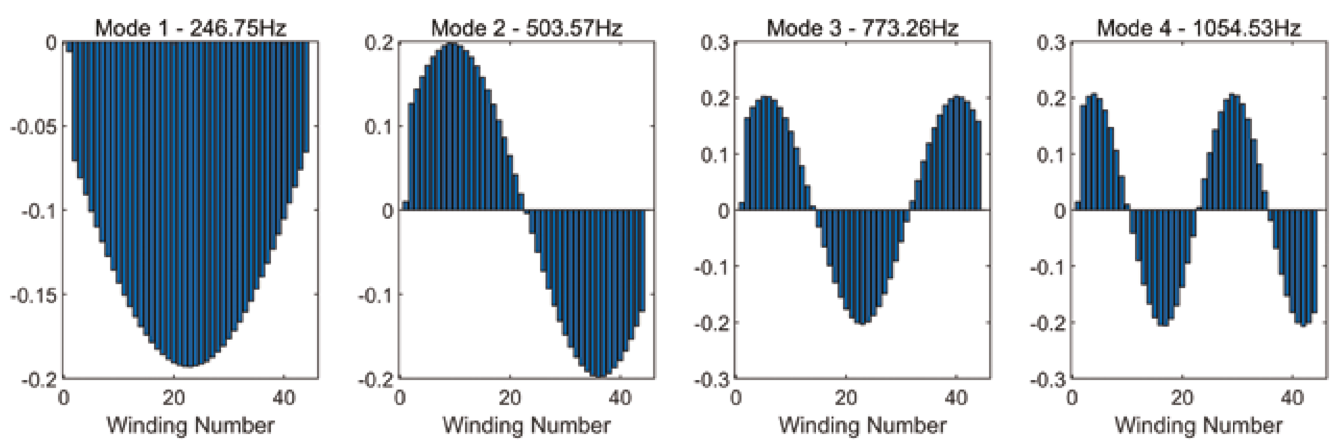


Figure 7. The first four mode shapes of winding axial vibration [17]

vibration characteristics are determined not only by the excitation of load current and voltage, but also the modal characteristics of the windings and core. Changes in the transformer's winding condition can be reflected from the changes in all or a

Natural frequencies of the transformer filled with oil are lower compared to the transformer without the oil since the oil acts as a mechanical damper

Table 1. Natural frequencies of windings in air and oil [18]

	In air	In oil
1	83.276	70.211
2	170.2	146.94
3	243.82	184.5
4	282.82	249.79
5	405.81	357.41
6	506.02	362.08

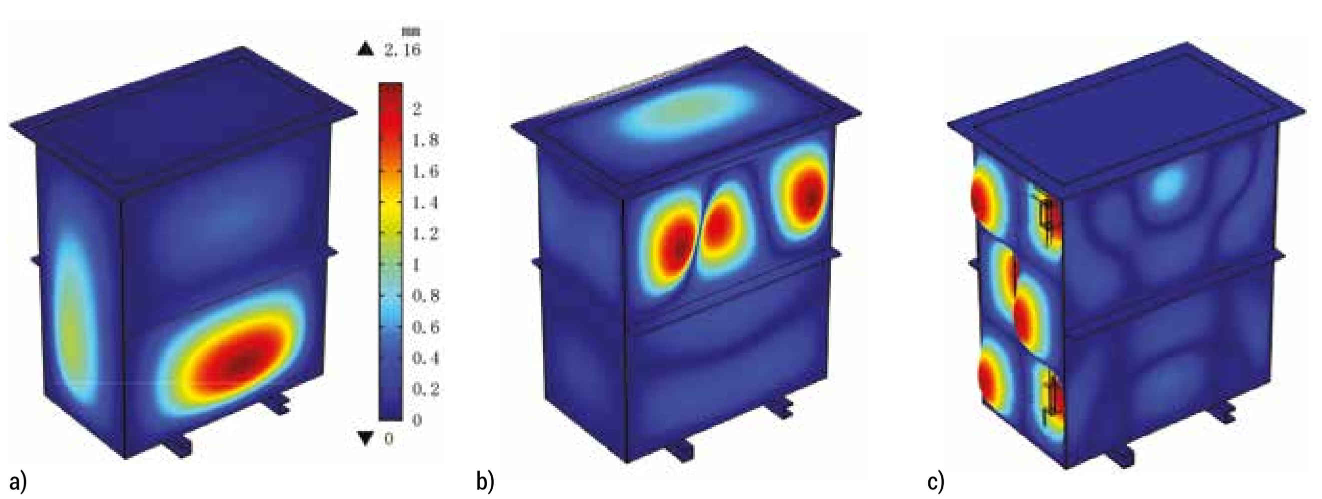


Fig. 8. Deflection of the oil-filled tank - a) static deflection, b) mode shape at 80.233 Hz, c) mode shape at 126.15 Hz [19]

The vibration-measurement-based condition monitoring systems aim to detect changes of modal characteristics of the windings under different conditions and to extract vibration features through the tank vibration signals

subset of its oscillatory modes. Therefore, the tank vibration signals can be used to monitor the changes in the transformer winding's mechanical condition.

5. Application of the vibro-acoustic signals in the winding mechanical condition monitoring

The vibration-measurement-based condition monitoring systems have been investigated since the 1990s. The two steps, as stated below, are investigating the changes of modal characteristics of the windings under different conditions and extracting vibration features through the tank vibration signals. The common causes of winding mechanical defects are: 1) winding looseness due to ageing, relaxation, shrinkage, and missing of pressboards; 2) the winding deformation caused by huge electromagnetic forces from short circuits. According to our previous investigations, the changes in natural frequencies corresponding to the type and causes of the defect are shown in Table 2.

Other than the changes of the vibration caused by mechanical defects, the influence of ageing, temperature, and moisture on the frequency response function (FRFs) of the windings' vibration is shown in Fig. 9.

The calculated FRFs of the transformer model clearly demonstrate that vibration characteristics of the test transformer winding are sensitive to transformer operating parameters. The data presented in Fig. 9 clearly demonstrate that the frequencies of the resonant peaks decrease with an increase of all the operating parameters, i.e., temperature, moisture content, and ageing time. Further, the variations in the frequencies of the low-frequency resonant peaks with changing operating parameters are lower than those of the high-frequency resonant peaks. For example, the difference between the frequencies of the 1st and 6th resonant peaks of FRFs corresponding to un-aged (DP1243 and DP1143) pressboard at 20 °C and 80 °C are 5 Hz and 43 Hz respectively. Similar behaviour in FRFs can be observed with ageing and moisture ingress (moisture content 2 %) as well. Further, the variations in the FRFs of un-aged pressboard with changing temperature are lower than those of the aged pressboard. On the other hand, the temperature sensitivity of the frequencies of the resonant peaks decreased with the moisture ingress. For example, the difference between the frequencies of the first resonant peak at 20 °C and 80 °C of FRFs corresponding to un-aged dry, un-aged wet, aged dry, and aged wet pressboard are 11 Hz, 3 Hz, 31 Hz, 5 Hz [20].

Experience shows the increase of the higher harmonics components of the vibrations in the old transformers compared with the new transformers

Based on the comprehensive understanding of the change of the windings' modal characteristics, several methods to extract vibration features were developed. These methods can be classified into two types according to the bandwidth of the vibration signals.

5.1 Vibration signals at discrete frequencies (multiple times of 50 Hz)

The fundamental frequency vibration signal has been widely used because of the clear relationship between acceleration and current and voltage. A common approach is to establish the relationship between 100 Hz acceleration and excitation (current and voltage), as shown in equation (1) [21], and compare the measured acceleration with the predicted values to assess the winding mechanical condition:

$$U_f = 10.37 + 12583.75 I^2 \qquad (1)$$

Table 2. The changes of natural frequencies corresponding to the type and causes of mechanical defects

Defects	Causes	Changes in natural frequencies
Overall looseness of the winding clamping pressure	Ageing, relaxation, plastic deformation of insulation material, damage of pressboard, winding collapse	Decrease of natural frequencies
Partial looseness of the winding clamping pressure	Conductor tilting, missing of pressboards, winding tilting and twisting	Decrease and splitting of natural frequencies
Deformation	Free buckling, forced buckling, axial bending	Increase in the number of natural frequencies

where U_f is the tank acceleration at 100 Hz, and I is the amplitude of load current.

Considering the vibration harmonics, researchers used the total harmonic distortion (THD), power spectrum density when assessing any changes in the windings' mechanical condition, as shown in Fig. 10. The THD is defined as:

$$THD = \sqrt{\sum_{n=2}^{N}\left(\frac{A_n}{A_1}\right)^2} \qquad (2)$$

where A_n is the n_{th} frequency of vibration harmonics, and A_1 is the fundamental frequency (twice the power of frequency) of the vibration signal.

It can be seen that the vibration harmonics at high frequencies increase in the old transformers compared with the new transformers.

The forced vibration signals at discrete frequencies of the transformer under electric excitation are composed of the

Transient vibration signals represent the broadband signal that contains a wide range of frequency bandwidth, which can reflect the modal characteristics of the core and the winding

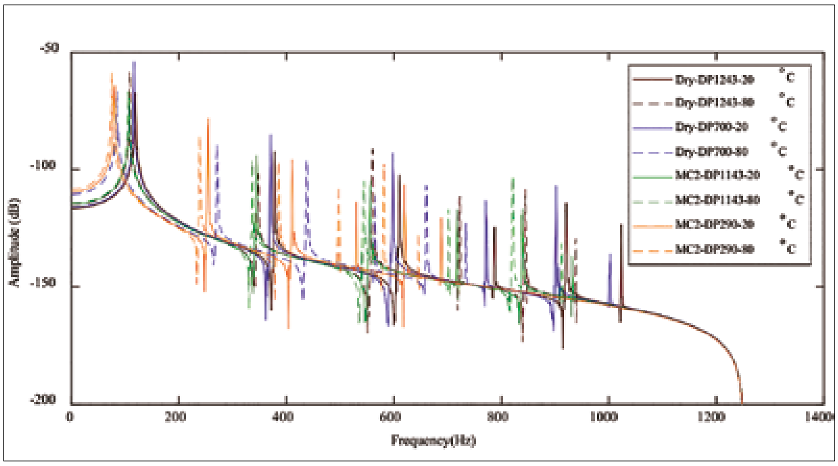


Figure 9. The influence of ageing, temperature, and moisture on the windings' vibration response [20]

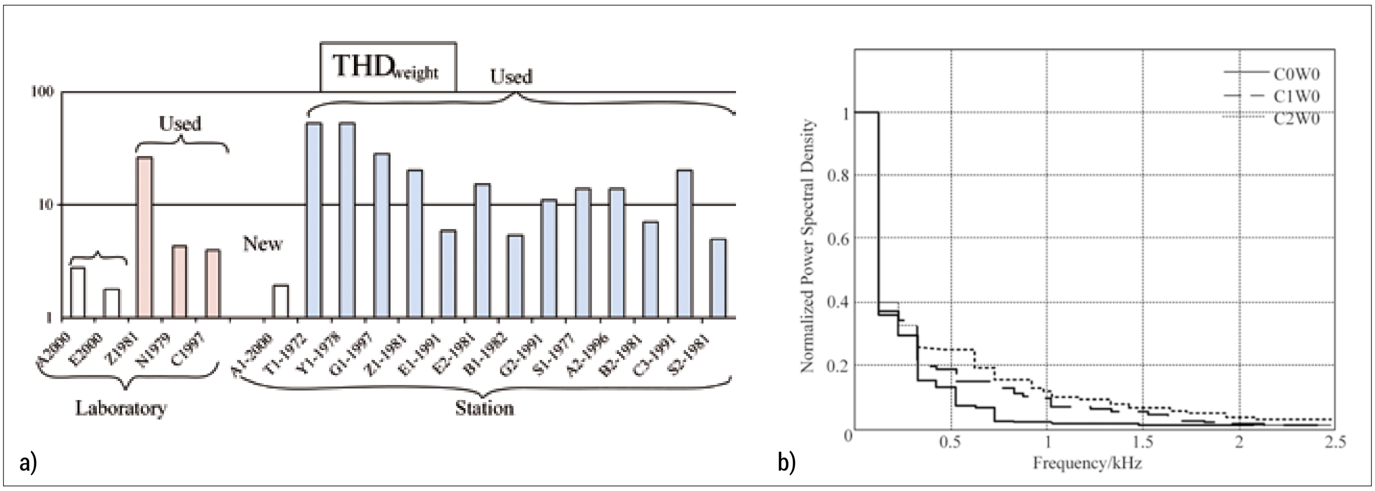


Figure 10. a) Examples of THD values evaluated for different transformers [6], b) normalised changes of the power spectral density of vibrations in a steady state of a transformer powered without load with core defects [13]

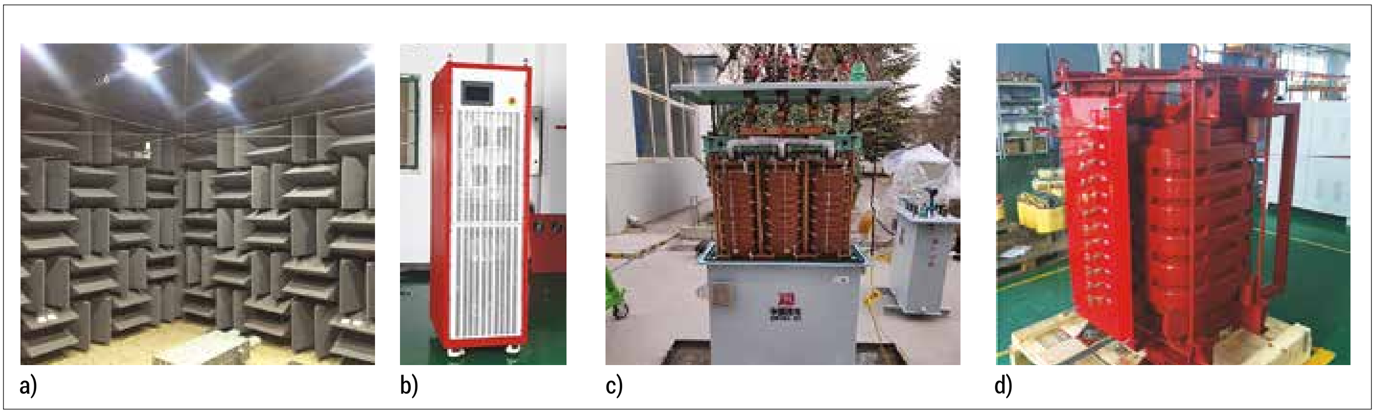


Figure 11. Experimental setup - a) semi-anechoic room, b) harmonic source, c) model transformer, d) the medium frequency transformer

The Hilbert transform and time-frequency analysis are used to deal with the transient vibration signals in multiple short-circuit tests

superposition of several independent vibration modes. When the windings' modal characteristics change, the discrete vibration frequency may not fully reflect the windings' modal characteristics. An effective approach is to extract the modal parameters of the winding by using broadband vibration signals.

5.2 Broadband vibration signals

Compared with the narrowband (fundamental frequency and multi-frequency) vibration signal, the broadband vibration signal contains a wide range of frequency bandwidth, which can reflect the modal characteristics of the core and the windings. When the transformer is excited by variable frequency voltage or the load current, the vibration frequency response function can be established and used in condition monitoring. To utilise such a methodology, an experimental setup consisting of the semi-anechoic room, harmonic sources, and model transformer is established, as shown in Fig. 11. To obtain the vibration frequency response of the windings, the harmonic voltages are applied to the winding in the load test. The obtained vibration response frequency function of a coil under different clamping pressures is shown in Fig. 12. In this figure, the amplitude of y-axis is defined as the acceleration at twice the current frequency divided by the current amplitude. Hence, the resonant peaks in Fig. 12 are corresponding to the windings' natural frequencies. The response curves at different clamping pressures illustrate the winding vibration excited by the harmonic current that can reflect the changes in mechanical properties.

When a transformer is switching on and off or suffered the external short circuit, the transient load current has broadband characteristics, as shown in Fig. 13. Hence, the broadband excitation can lead to a broadband vibration to reflect the modal characteristics. The Hilbert transform and time-frequency analysis are used to deal with the transient vibration signals in multiple short-circuit tests, as shown in Fig. 14. It can be observed that the vibration harmonics at high-frequency increase during the multiple short-circuit tests.

Apart from the analysis of transient vibration signals, random vibrations excited from environmental sources (machinery operation, cooling system, and other nearby disturbances) and internal sources of transformers also exhibit broadband responses. Hence, the methodology of separating the vibration harmonics and random vibration signals, analysing the weak random vibration signals is adopted. After obtaining the weak vibration signals, the operation modal analysis is used to extract modal parameters through broadband vibration signals. The obtained natural frequencies and mode shapes are shown in Fig. 15, which coincide with the results in Fig. 7.

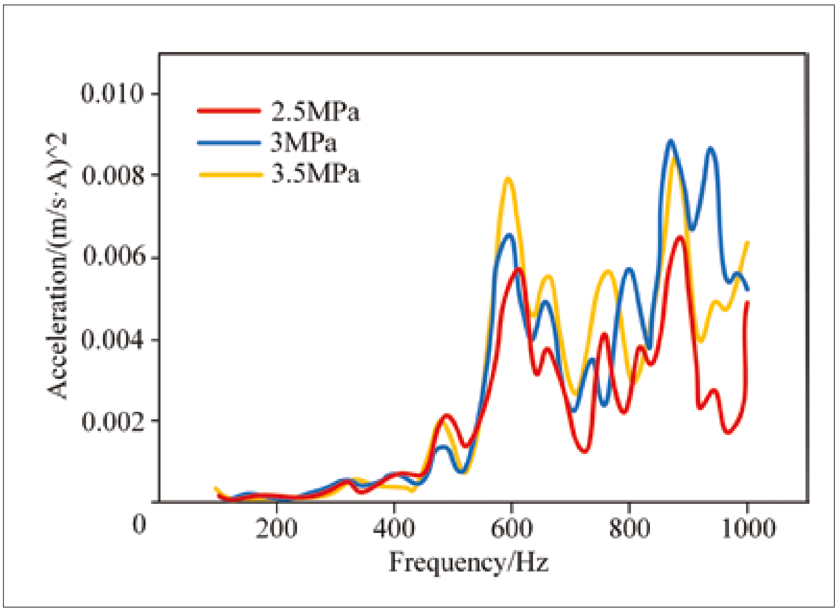


Figure 12. Vibration frequency response function of the winding under the excitation of harmonic sources

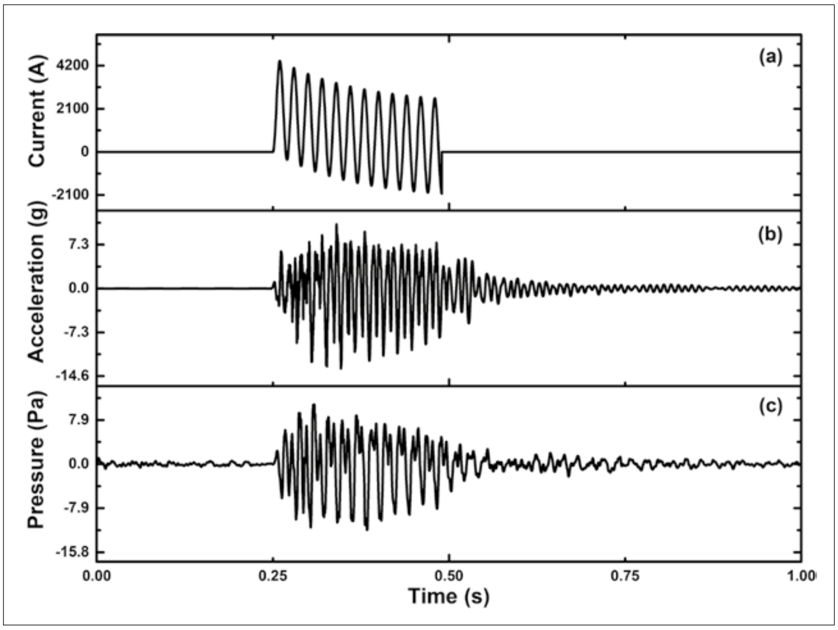


Figure 13. Transient vibration and acoustic signals of a transformer during the short circuit tests [22]

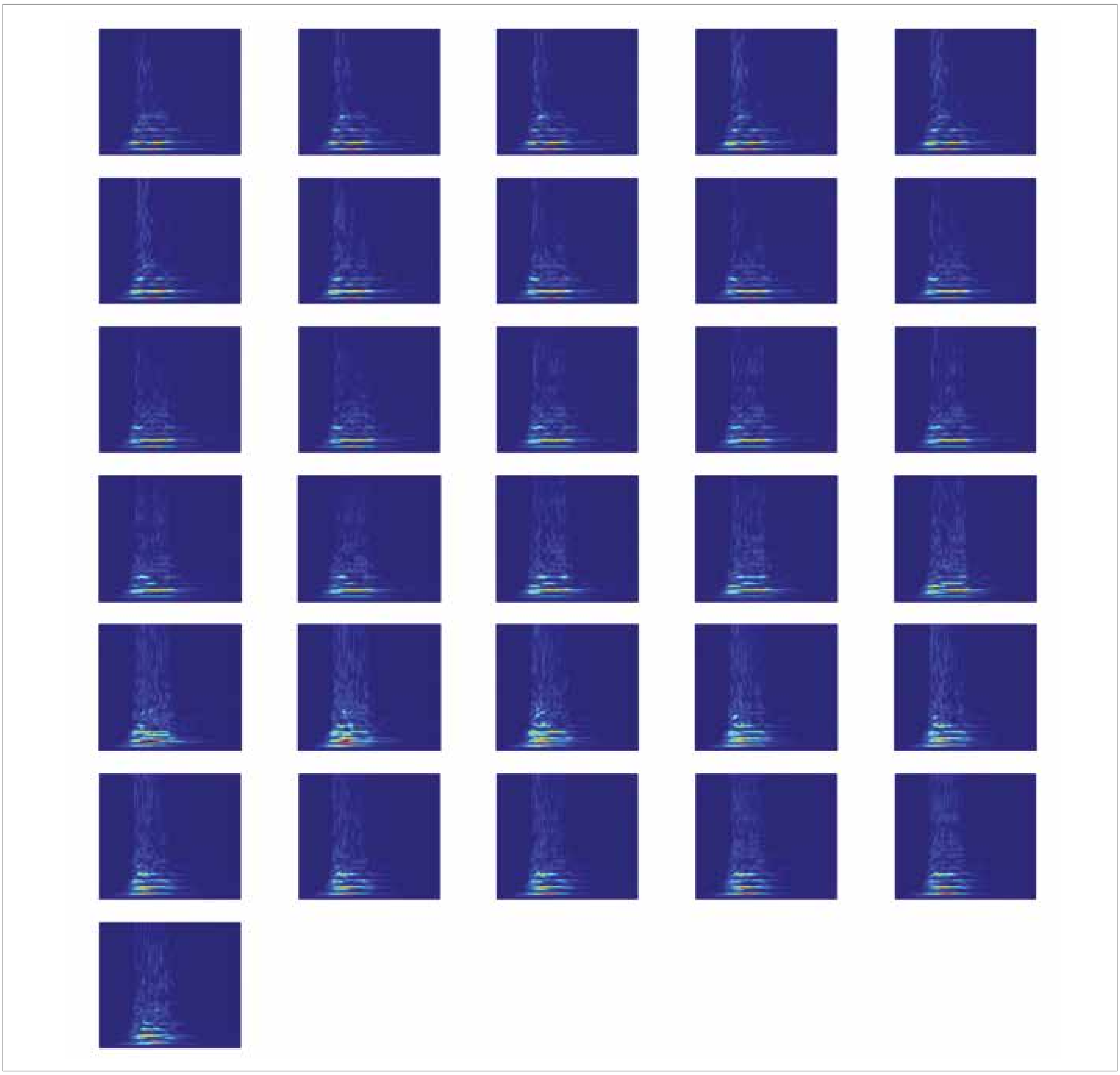


Figure 14. Time-frequency spectrum of a transformer during the short circuit tests [22]

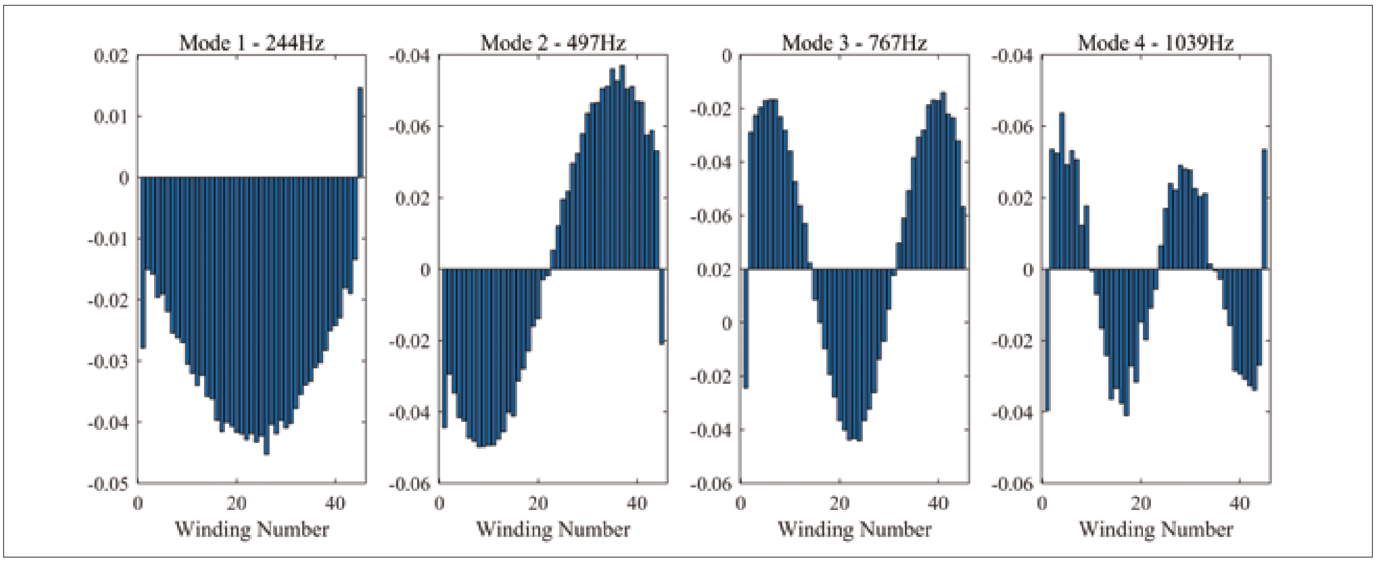


Figure 15. The first four mode shapes and natural frequencies obtained by OMA in the presence of harmonics [17]

Random vibrations also exhibit broadband responses, and they originate from environmental sources (machinery operation, cooling system, and other nearby disturbances), or from internal transformer's sources

6. Conclusion

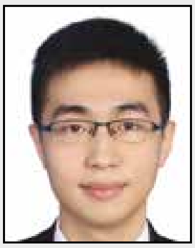
The article presents the 20 years of efforts of researchers in Xi'an Jiaotong University and The University of Queensland on transformer vibration characteristics and its application in the winding mechanical condition monitoring. The conclusion is as follows:

1. Winding vibration characteristics are highly complicated, consisting of the overall vibration of the winding disks and the local vibration of the conductors. Therefore, both vibration patterns should be considered.
2. Stress relaxation, ageing, plastic deformation of insulating material, damage of clamping rings, and falling off spacer could lead to the decrease of winding axial clamping pressure and natural frequency, while the winding deformation could lead to an increasing number of natural frequencies.
3. Transformer vibration characteristics are highly affected by the operating condition (e.g., operating flux density, load current, etc.) and structure parameters. As such, a "before-and-after" approach can be adopted for online winding condition monitoring. It makes a diagnosis based on the comparison between the current vibration measurement data and the historical vibration measurement data.

Authors

Fan Zhang was born in Shaanxi Province, China in 1991. He received the BS. and PhD degrees in electrical engineering in 2014 and 2019 from Xi'an Jiaotong University, respectively. From 2018 to 2019, he worked as a joint Ph.D. student in the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Australia. He is currently an assistant professor with Xi'an Jiaotong University. His research interest is in multiphysics modelling and condition monitoring of power equipment, and signal processing.

Shengchang Ji was born in Shandong Province, China in 1976. He received the BSc and PhD degrees in electrical engineering from Xi'an Jiaotong University, China in 1998 and 2003, respectively. He is currently a professor with Xi'an Jiaotong University. His research work includes investigations on vibro-acoustics characteristics and condition monitoring of power equipment.



Yuhang Shi was born in Shaanxi Province, China, in 1994. He received the BSc and PhD degrees in electrical engineering from Xi'an Jiaotong University in 2015 and 2020, respectively. Currently, he is an engineer working in Shaanxi Electric Power Research Institute. His research interest mainly focuses on the condition monitoring of power transformers.

Hui Ma (M'95-SM'16) received BEng and MEng degreess in Electrical Engineering from Xi'an Jiaotong University, Xi'an, China, in 1991 and 1994, respectively; MEng (by research) in Electrical Engineering from Nanyang Technological University, Singapore in 1998; and PhD in Electrical Engineering from the University of Adelaide, Adelaide, Australia, in 2008. Currently, he is a lecturer in the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Australia. Dr. Ma has seven years of industry experience. His research interests include industrial informatics, condition monitoring and diagnosis, power systems, wireless sensor networks, and sensor signal processing.

Bibliography

[1] E. Reiplinger, *Study of noise emitted by power transformers based on today's viewpoint,* Paris: 1988

[2] H. Zhou, K. Hong, H. Huang, *Transformer winding fault detection by vibration analysis methods*, Applied Acoustics, 114: 136-46, 2016

[3] K. Hong, H. Huang, J. Zhou, *Winding condition assessment of power transformers based on vibration correlation*, IEEE Trans Power Delivery, 30(4): 1735-45, 2015

[4] K. Hong, H. Huang, J. Zhou, *A vibration measurement system for health monitoring of power transformers*, Measurement, 93: 135-47, 2016

[5] K. Hong et al., *A method of real-time fault diagnosis for power transformers based on vibration analysis*, Meas Sci Technol, 26(11): 115011, 2015

[6] C. Bartoletti, M. Desiderio, D. Carlo, *Vibro-acoustic techniques to diagnose power transformers*, IEEE Trans Power Delivery, 19(1): 221-9, 2004

[7] M. Bagheri, A. Zollanvari, S. Nezhivenko, *Transformer fault condition prognosis using vibration signals over cloud environment*, IEEE Access, (6): 9862-74, 2018

[8] M. Bagheri et al., *A new vibration analysis approach for transformer fault prognosis over cloud environment*, Int J Electr Power Energy Syst, 100: 104-16, 2018

[9] Y. Shao, et al., *The fault detection of transformer windings' deformation based on Vibration frequency response analysis,* in Proc. ICQRMSE*,* Chengdu, China, pp. 713–718, 2012

[10] Y. Wang, J. Pan, *Comparison of mechanically and electrically excited vibration frequency responses of a small distribution transformer*, IEEE Trans. Power Delivery, Vol 32, No 3, pp. 1173-1180, June, 2017

[11] Y. Wang, J. Pan, *Applications of operational modal analysis to a single-phase distribution transformer*, IEEE Trans. Power Delivery, Vol 30, No 4, pp. 2061-2063, August 2015

[12] S. Borucki, *Diagnosis of technical condition of power transformers based on the analysis of vibro-acoustic signals measured in transient operating conditions*, IEEE Trans. Power Delivery, Vol 27, No 2, pp. 670–676, April 2012

[13] E. Kornatowski, S. Banaszak, *Diagnostics of a transformer's active part with complementary FRA and VM measurements*, IEEE Trans. Power Delivery, Vol 29, No 3, pp. 1398-1406, June 2014

[14] S. Banaszak, E. Kornatowski, *Evaluation of FRA and VM measurements complementarity in the field conditions*, IEEE Trans. Power Delivery, Vol 31, No 5, pp. 2123-2130, October 2016

[15] R. Penin et al., *Estimation of relative magnetostriction and Maxwell's forces in stacked Grain Oriented steel structures*, Proceedings of International Conference on Electrical Machines, Sapporo, Japan, IEEE 2012

[16] B. Weiser, H. Pfutzner, J. Anger, *Relevance of magnetostriction and forces for the generation of audible noise of transformer cores*, IEEE Transactions on Magnetics, 36(5): 3759-3777, 2000

[17] F. Zhang et al., *Operational modal analysis of transform windings*, IEEE Transactions on Power Delivery, Vol 35, No 3, pp. 1285-1298, 2020

[18] F. Zhang, et al., *Comprehensive vibration generation model of transformer winding under load current*, IET Generation, Transmission & Distribution, Vol 19, No 9, pp. 1563-1571, 2019

[19] F. Zhang et al., *Investigation on the vibration source and transmission characteristics in power transformers*, Applied Acoustics, Vol 151, pp. 99-112, 2019

[20] WMLB Naranpanawe, *Understanding the moisture temperature and ageing dependency of power transformer winding clamping pressure*, Brisbane, University of Queensland, 2018

[21] S. C. Ji, Y. F. Luo, Y. M. Li, *Research on extraction technique of transformer core fundamental frequency vibration based on OLCM*, IEEE Transactions on Power Delivery, Vol 21, No 4, pp. 1981-1988, 2006

[22] Y. H. Shi et al., *Multi-Frequency Acoustic Signal Under Short-Circuit Transient and Its Application on the Condition Monitoring of Transformer Winding*, IEEE Transactions on Power Delivery, Vol 19, No 1, pp. 221-229, 2019

Authors

Tapan Kumar Saha (M'93- SM'97-F'2019) was born in Bangladesh and immigrated to Australia in 1989. He received his BSc, MTech, and PhD in engineering from the Bangladesh University of Engineering and Technology, the Indian Institute of Technology, New Delhi, and the University of Queensland, respectively. Tapan is currently a professor of electrical engineering in the School of Information Technology and Electrical Engineering, University of Queensland, Australia. He is a fellow of the Institution of Engineers, Australia. His research interests include condition monitoring of electrical plants, energy management, and renewable energy integration to the grid.

Chandima Ekanayake received his BScEng, TechLic and PhD from the University of Peradeniya, Sri Lanka and Chalmers University of Technology Sweden, respectively. From 2006 to June 2008 he was attached to the department of Electrical and Electronic Engineering, University of Peradeniya, Sri Lanka, as a senior lecturer. In 2008, he joined the University of Queensland as a post-doctoral research fellow to work on an ARC funded project on improving transformer insulation diagnostics through polarisation measurements. Currently, he is a senior lecturer in the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Australia. His research experience and interests include condition monitoring of power apparatus, alternatives for insulating oil, performance studies of HV insulators and energy related studies.

Lakshitha Naranpanawe received BSc and PhD in electrical engineering from the University of Peradeniya, Sri Lanka and the University of Queensland, respectively. Currently, he is a research fellow in the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Australia. Prior to joining the University of Queensland, Lakshitha has worked as an electrical engineer at a hydro power station at Ceylon electricity board, Sri Lanka. His research interests include condition monitoring and diagnosis, finite element modelling for condition monitoring applications, and energy data application for electricity grid management.